HF Radar Measurements of Ocean Surface Currents and Winds

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LONG-TERM GOAL

Our long term goal is to develop multifrequency, high frequency (HF) radar techniques and instrumentation for measuring surface currents, vertical shear, winds, friction velocity and waves in coastal regions and large lakes for scientific, civil and military applications. Our goal includes deployment of HF radar systems for air-sea interaction, coastal oceanography and ship detection research as well as the integration of HF radar measurements into coastal ocean models. A related goal is to investigate and develop ship detection and tracking techniques for multifrequency HF radar.

OBJECTIVES

The objectives of this project began with the construction and deployment of two and later three multifrequency HF radar instruments (called MCR for Multifrequency Coastal Radar) to Monterey Bay, California. Further experiment deployments were to the Virginia coast and to Lake Michigan for fresh water experiments (NSF sponsorship). The data collected at these sites is reduced, analyzed and interpreted to achieve the specific research objectives listed below:

1. Improvement of radar performance by upgrading hardware and software and developing improved transmit antennas, signal processing and flexible use of multiple frequencies

2. Improvement of HF radar estimates of surface currents, vertical shear, winds, friction velocity and waves by improved estimation algorithms that use knowledge of air-sea interaction physics

3. Estimate surface wind speed and direction using multifrequency HF radar measurements by exploiting air-sea interaction physics and HF radar measurements of vertical current shear

4. Ocean science investigations, including assimilation of HF radar data into coastal ocean models for circulation, chemical and biological properties as well as air-sea interaction studies

5. Use of continuing HF radar observations on Monterey Bay in observing ships to assess the usefulness of multiple frequency HF radar in ship detection and tracking.

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14. ABSTRACT
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APPROACH

This project requires an expert team of engineers and oceanographers from many institutions, including Peter Hansen and Lorelle Meadows (University of Michigan), Calvin Teague (Stanford University), Dan Fernandez (California State University, Monterey Bay), Jeff Paduan (Naval Postgraduate School) and Kenneth Laws, Jessica Drake and Steve Petersen (University of California at Santa Cruz). This team designed, constructed, upgraded and deployed MCRs at sites on the Atlantic and Pacific oceans as well as the Great Lakes. We continually seek to deploy MCR systems for air-sea and ship observations in both short campaigns and long-term observations. A summary follows:

1. **Ocean science investigations**: participate in investigations of air-sea interaction, including momentum transfer and structure of the air and sea boundary layers and the assimilation of HF radar data into the coastal ocean circulation models

2. **Improve radar performance** by upgrading radar hardware and software, repairing and upgrading the radar antennas, especially transmit antennas; and comparing MCR with other HF systems

3. **Improve HF radar estimates of surface currents, current shear, winds and friction velocity** by developing improved estimation algorithms that use air-sea interaction physics, e.g., the Charnock relation, and continued work on MUSIC, rootMUSIC and beamforming

4. **Estimate surface wind vectors using multifrequency HF radar** measurements by using statistical techniques, air-sea interaction theory and the HF vertical current shear measurements

5. **Use the continuing HF radar observations on Monterey Bay to observe ships** (especially known ships at known locations) at multiple HF frequencies, noting changes in detection and tracking performance with frequency, range, direction, ship type, etc.

WORK COMPLETED

1. **Observational program:** We strive to keep the MCR units in operation either at Monterey Bay, their 'home site', or employed in experimental campaigns elsewhere. During the last year two MCRs operated on and near Monterey Bay. This includes monitoring, maintenance and upgrades.

2. **Estimation of wind friction velocity (u*) using multifrequency HF radar:** Multifrequency HF radar observations of currents at different depths are used to find u* – see Meadows (2002).

3. **Evaluation of Root-MUSIC processing for HF radar:** We assessed the usefulness of this specialized form of MUSIC processing for linear HF radar antenna arrays – see Teague (2002).

4. **Comparison of MCR and SeaSonde measurements of surface currents on Monterey Bay CA:** We compared surface current measurement results of MCR and SeaSonde (CODAR Ocean Systems instrument) systems using data from co-located sites – see Vesecky et al. (2001 & 2002).

5. **Retrieval of vector winds using multifrequency HF radar measurements:** Partial least squares estimation to estimate vector winds; estimates were compared to buoy measurements.

6. **Communication of research results:** This year we presented eight papers at four major conferences and workshops on remote sensing and oceanography, including IGARSS and the Radio Oceanography Workshop, sponsored by ONR. One refereed journal paper was published.

7. **Ph. D. student graduated:** We are pleased that Lorelle Meadows received her Ph. D. degree in June 2002 from the University of Michigan (see Meadows, 2002 below).

RESULTS

This year produced many new results with the analysis of past field observations as well as collection of new data. Below are two examples that are particularly important to the field. One concerns the retrieval of friction velocity from multifrequency HF radar observations and comparison with buoy measurements and the other concerns the prediction of vector winds using HF radar data.

During the MUSE experiment of Autumn, 2000 multifrequency coastal radars (MCRs) at Moss Landing and Santa Cruz on California's Monterey Bay made HF measurements that covered the location of the NPS flux buoy near the Moss Landing radar site. This buoy was capable of measuring friction velocity in the air as well as other air-sea interaction parameters. As her Ph. D. thesis project, Lorelle Meadows used data from these radars as well as the flux buoy to develop and test a technique for retrieving friction velocity from MCR measurements. The approach to the friction velocity measurement begins by assuming that the vertical current profile follows the logarithmic (law of the wall) theory for a turbulent boundary. Although there is some controversy regarding a linear variation close to the surface and experiments to support both the linear and the logarithmic views, the difference is not critical to this method. The fundamental direct measurement of the HF radar is the Doppler shift and hence the phase velocity of the radially traveling Bragg resonant waves on the ocean surface, i.e., ocean waves at wavelengths of ≈ 6.9, 11.2, 22.1 and 31.3 m. The Bragg resonant waves traveling radially with respect to the radar are half the radar wavelength and give rise to the HF radar echoes. The phase velocity (c_p) of surface waves affected by near surface currents can be estimated to first order by a weighted integral over depth z of the vertical current profile U(z), $c_p = (g/k)^{0.5} + dc$ where $dc = 2k \int U(z)\, e^{2kz}\, dz$, where k is the wavenumber of the Bragg resonant ocean wave and $g = 9.8$ m/s^2. The law of the wall says that U(z) depends on friction velocity in the water u_{*w} and roughness length, z_o.

The Levenberg-Marquart nonlinear estimation technique is used to find values of u_{*w} and z_o which minimize the differences between the observed and predicted values of c_p. Once u_{*w} is estimated, u_{*a} in the air can be found knowing that u_* scales with density, $u_{*w} = (r_a / r_w)^{0.5}\, u_{*a}$. Thus, HF estimates and buoy estimates of friction velocity can be compared. Note that this method does not rely on an effective depth estimate for HF radar currents, but uses the Doppler observations directly.

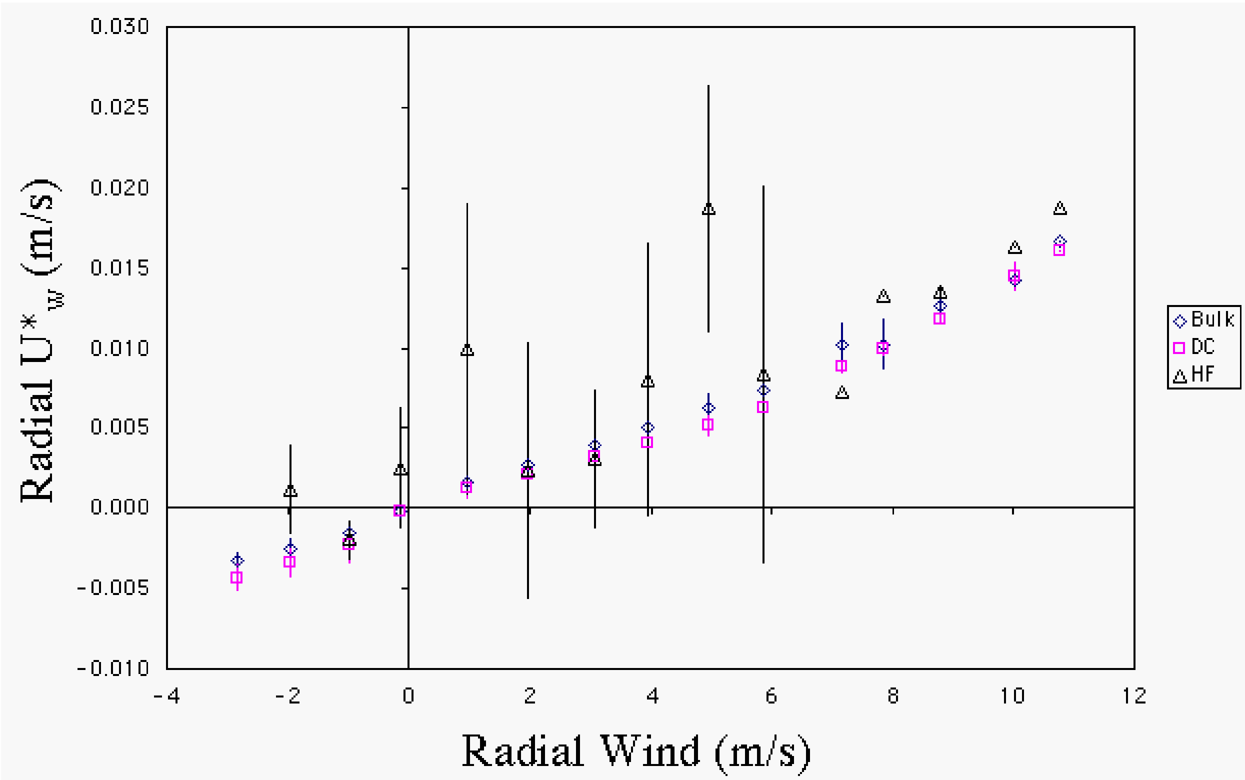

Fig. 1. Comparison of estimates of u_{*a}. The colored square and diamond are estimates from the NPS flux buoy using a <u>bulk</u> parameter estimation, using air-sea measurements, and a direct calculation (DC), found by direct correlation of wind field fluctuations. The multifrequency coastal radar (MCR) estimates are made as described in the text. Radial refers to along the HF radar line of sight, i.e., all the u* estimates are projected onto this line of sight.

For wind speeds above ≈ 6 m/s the HF radar estimates agree very well with the buoy measurements. At lower wind speeds one expects poorer results from the MCR because other factors, such as tides and buoyancy flows, are affecting the near surface currents and are presently ignored in the analysis. At any wind speed this method produces values of χ^2, which tells one how well the model fits the measurements, and hence allows one to put error bars on the measurements. Note that aside from one case the buoy measurements are within the error bars of the MCR estimates. *We regard these results as very promising for the use of multifrequency coastal radar in mapping friction velocity.*

Multifrequency HF radar measurements reveal the vertical current shear near the ocean surface. Thus, we anticipate that wind speed and direction can be estimated from MCR data since wind stress on surface is usually the dominant factor in determining current magnitude and the vertical shear. Previous research has been successful in making wind direction estimates, but no really successful estimates of wind speed. In this study we did not try to employ a physical model as above, but for this initial effort choose a linear, empirical prediction method known as partial least squares. This method seeks a wind component estimate based on a weighted sum of all the input data components. The weights are determined by a least squares procedure. For the input data we used the surface currents at all depths as well as the wind direction estimated by the relative strengths of the first order Bragg peaks in echo Doppler spectrum. Weights derived by the partial least squares algorithm emphasized the following:

1. Input data from the highest radar frequencies, sensing nearest the surface, were most important.

2. Differences between currents estimated from radar data at two different frequencies were important – this reflects the importance of shear in the wind estimates.

3. Direction estimates from Bragg line ratios were important – this ratio estimates the wind direction as established by a number of investigators in earlier work.

The results are impressive with the standard error of measurement, i.e., the standard deviation of the difference between HF and buoy measurements, being very near 1 m/s after removal of a very small bias, ≈ 10 cm/s. This level of estimation accuracy is sought by meteorologists, but seldom attained in remote sensing measurements. Further, the method does not appear to degrade at low wind speeds.

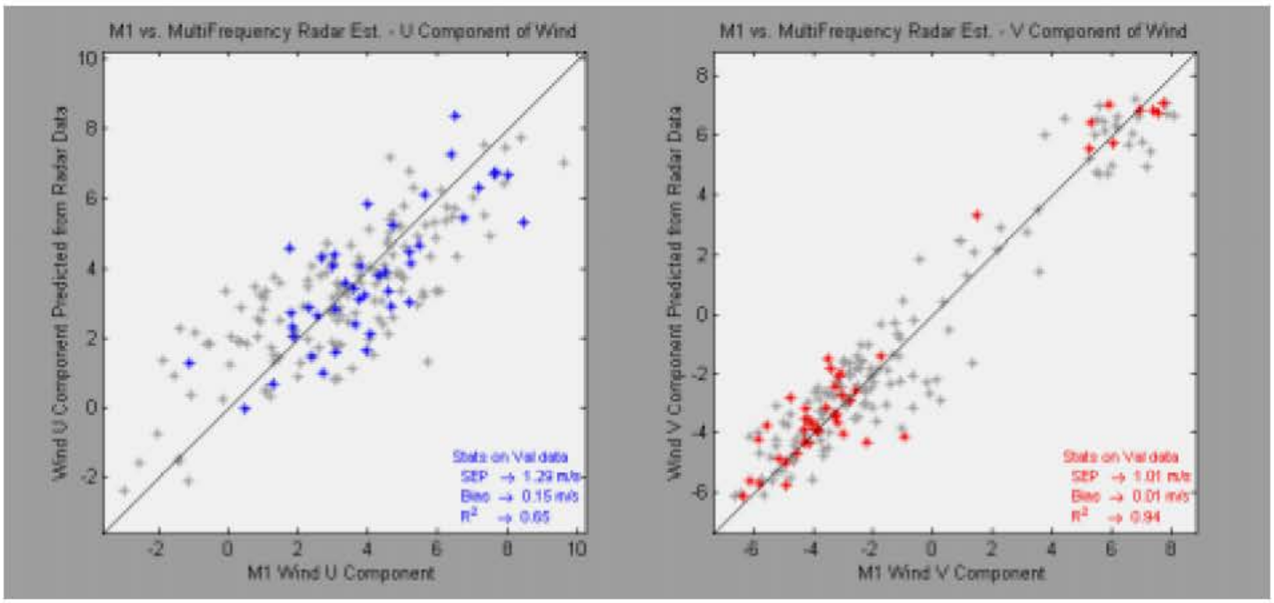

Fig. 2. Comparison of wind speed estimates from MCR with buoy winds. The standard error of prediction SEP is ≈ 1 m/s and bias ≈ 10 cm/s. Left (right) panel shows eastward (westward) U (V) component of the wind. Colored points are MCR estimates, whereas the gray points are the training set used to develop the partial least squares estimation algorithm.

IMPACT/APPLICATION

Multifrequency HF radars have demonstrated their usefulness in measuring surface currents and current shear in the top few meters of the ocean. No other technique makes such measurements over a large area, at such low cost. We extended HF radar applications to fresh water and to mapping of friction velocity and wind vector. HF radar measurements are useful for real time applications.

RELATED PROJECTS

1. We participated in the Integrated Coastal Ocean Network (ICON) project (National Ocean Partnership Program), integrating in situ and remote measurements over Monterey Bay.

2. We began participation in the Center for Integrated Marine Technology that brings together physical, chemical and biological oceanographers as well as marine biologists to make and interpret measurements relevant to the Monterey Bay Marine Sanctuary (NOAA)

PUBLICATIONS

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Teague, C. C., Root-MUSIC processing of multifrequency coast radar data

Vesecky, J. F., MCR and SeaSonde Comparison

Vesecky, J. F., Vector winds from multifrequency HF radar